Six-dimensional ionization cooling: options, issues and R&D (MICE)

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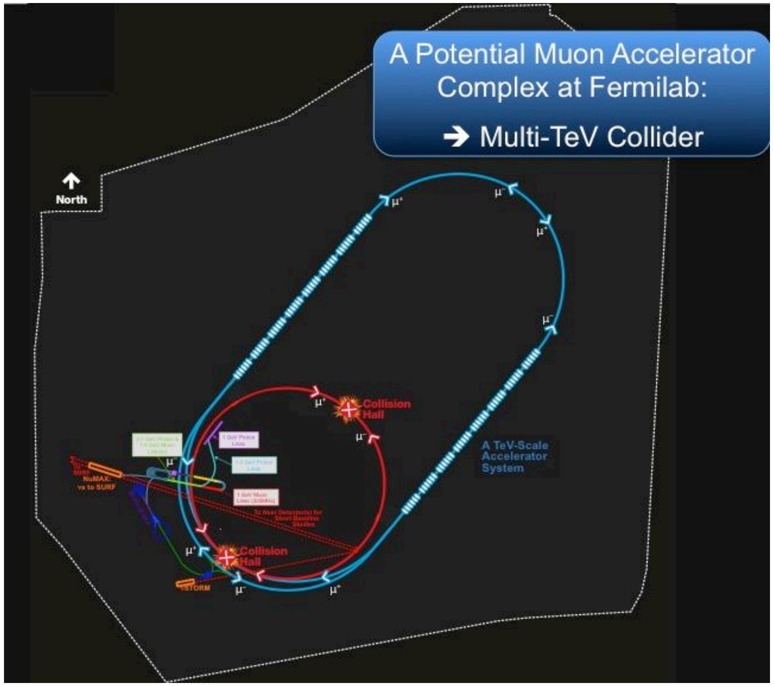
July 15, 2014

Outline

- Motivation
- Ionization cooling
- Six-dimensional (6D) cooling
- Cooling stages and options
- Issues
- R&D: MICE
- Summary

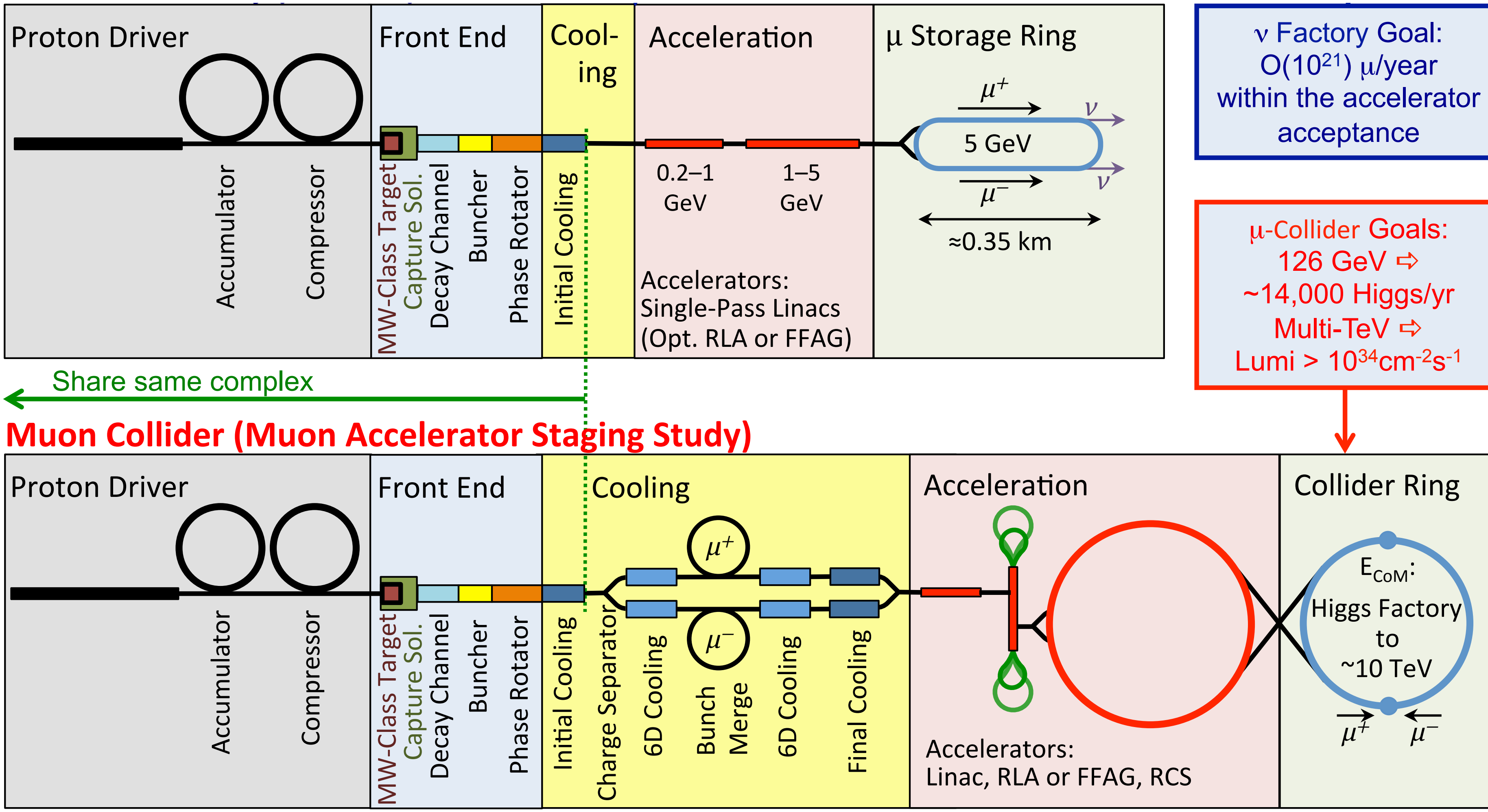
Muon advantages and challenges



- (+) Muons are elementary particles, clean collisions at full energy. Advantage over protons where only fraction of the energy goes into quark-quark collisions.
- (+) Muons are much heavier than electrons, no bremsstrahlung issue. Compact footprint.

(-) Muons decay (τ=2.2 μs at rest), need to be focused and accelerated fast.
(-) Tertiary production results in large phase space volume, need beam size reduction (=cooling).

Introduction: NF & MC

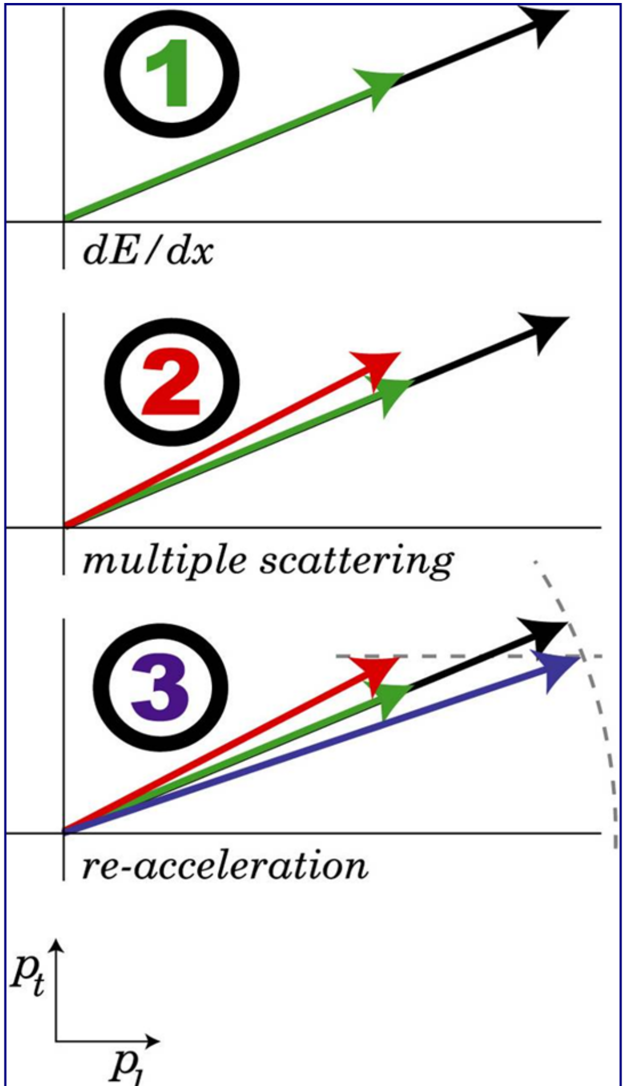


- Schematics of the neutrino factory (top) and muon collider (bottom)
- Initial collection and cooling are the same in both machines

Ionization cooling

- NF/MC are tertiary beam machines (p ➔ π ➔ μ). Emittances coming out of the target are very large.
- Need intense μ beam ➔ need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive ➔ for cost-efficiency need to cool the beam prior to accelerating.
- NF requires a modest amount of initial 6D cooling.
- MC designs assume significant, $O(10^6)$ six-dimensional cooling.
- Need to act fast since muons are unstable. The only feasible option is ionization cooling.

Ionization cooling

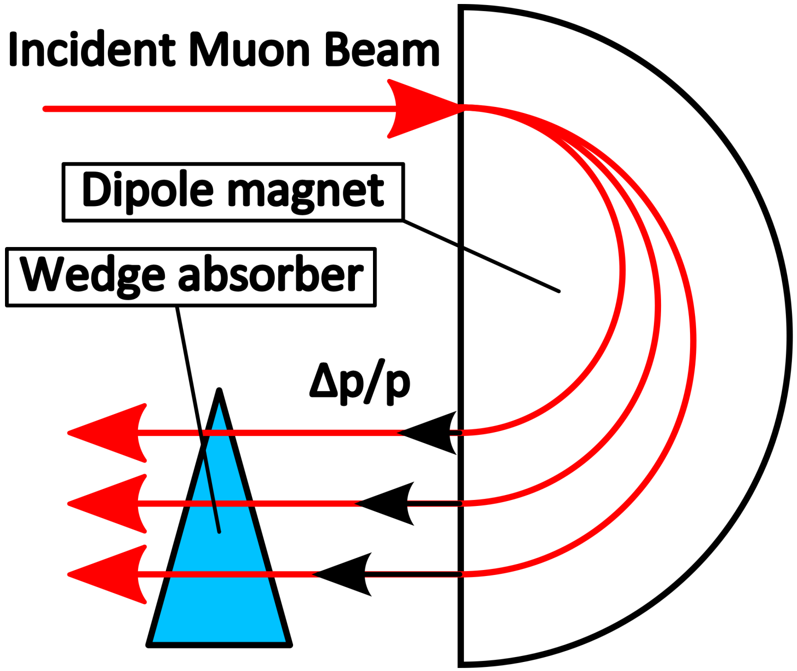


$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

- $d\epsilon_n/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material (all three components of the particle's momentum are affected).
2. Unavoidable multiple scattering (can be minimized by choosing the material with large X_0, hence, low Z.
3. Re-accelerate to restore energy lost in material. Only the longitudinal component of momentum is affected.

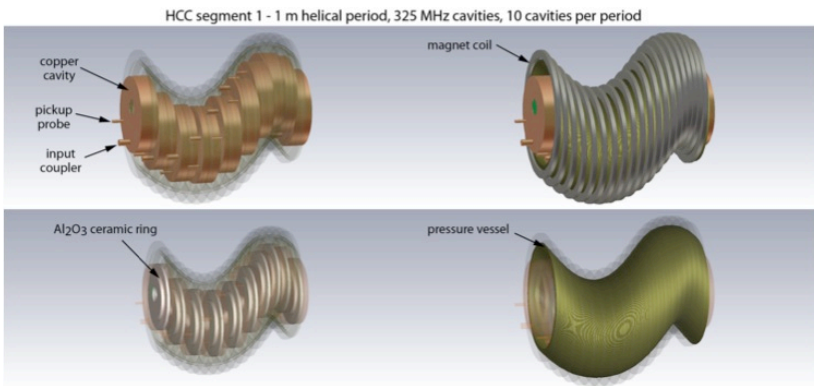
6D cooling via emittance exchange

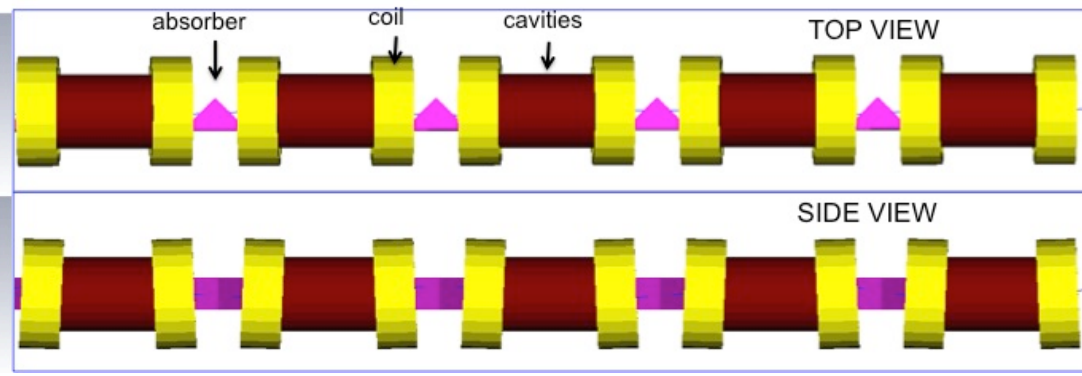


- Emittance exchange principle: instead of letting the beam with zero dispersion through a flat absorber, we introduce dispersion and let the particles with higher momentum pass through more materials, thus reducing the beam spread in the longitudinal direction.
- Another option would be to control particle trajectory length in a gas-filled channel.
- See also next talk by Diktys Stratakis.

MAP IBS process

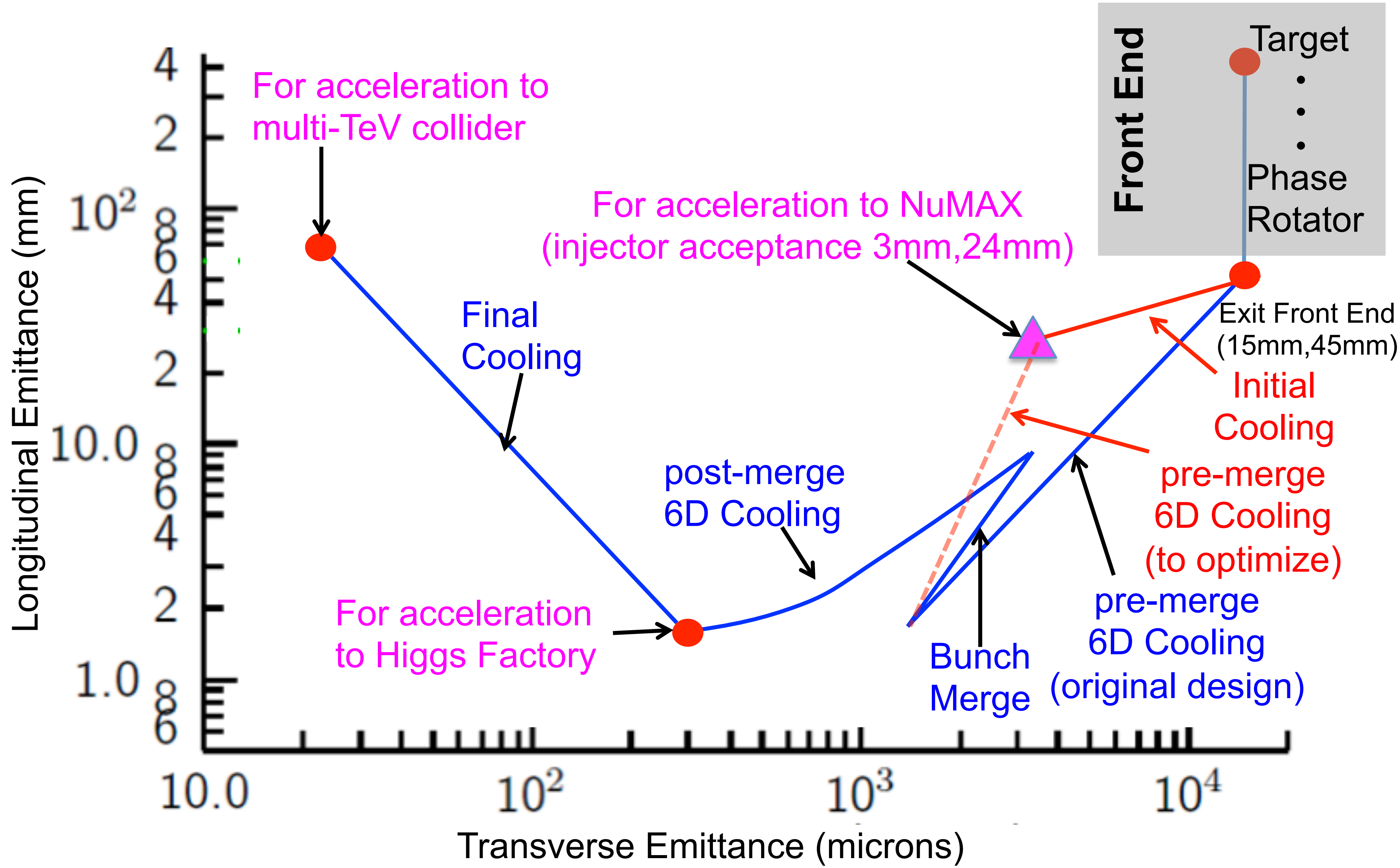
- MAP: Muon Accelerator Program formed in 2010 to unify the DOE supported R&D in the U.S. aimed at developing the concepts and technologies required for muon colliders and neutrino factories.
- IBS: Initial Baseline Selection process aimed at producing initial designs of all key accelerator systems for muon-based neutrino factories and colliders.



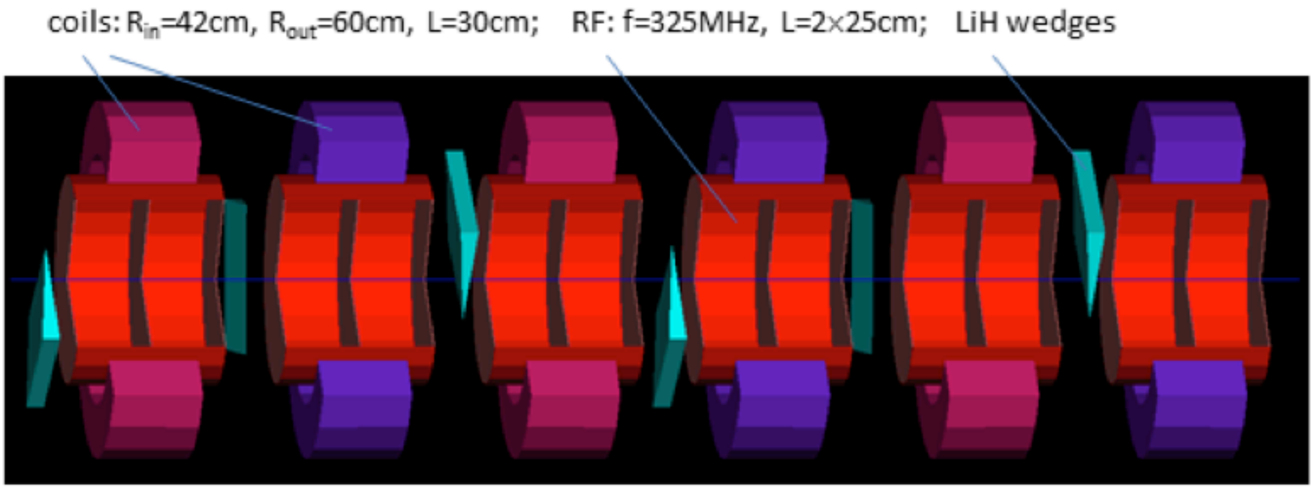


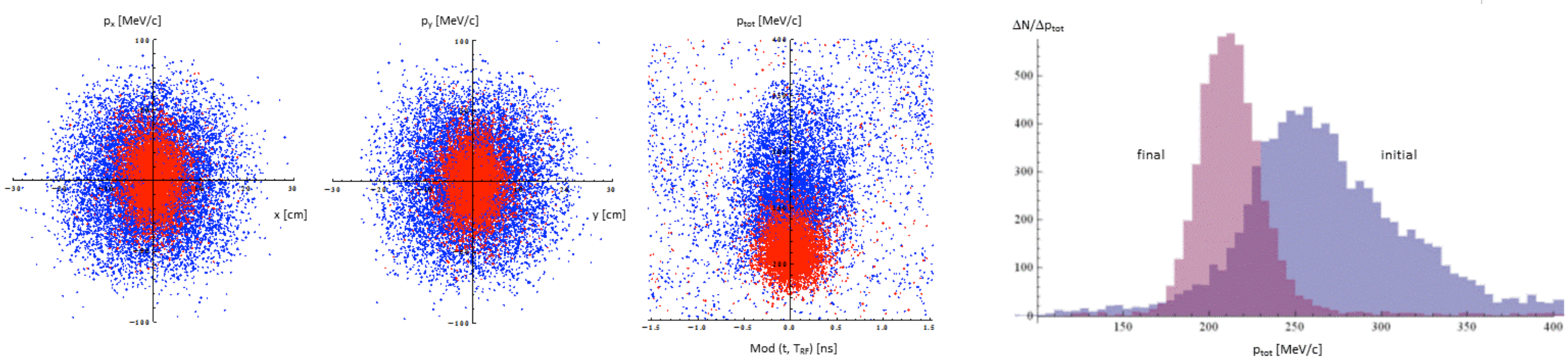
- We have two key alternatives we are pursuing for the 6D cooling channels.
- Left: high-pressure gas-filled RF helical cooling channel (HCC).
- Right: vacuum RF rectilinear cooling channel (VCC).
- IBS encompasses other systems as well: in particular, initial cooling channel, bunch merging, charge separation, and final cooling.

Cooling scheme overview



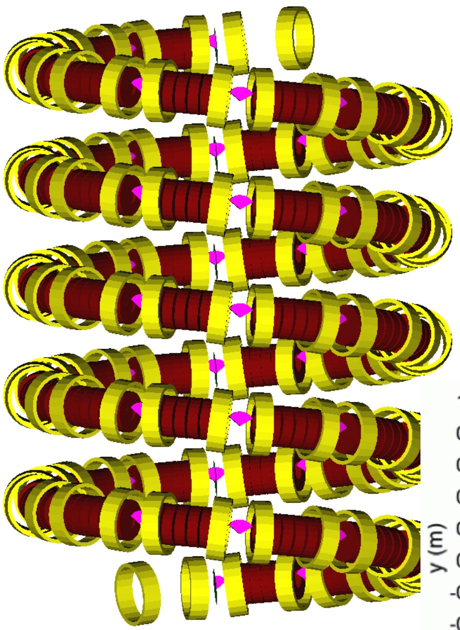
Initial cooling

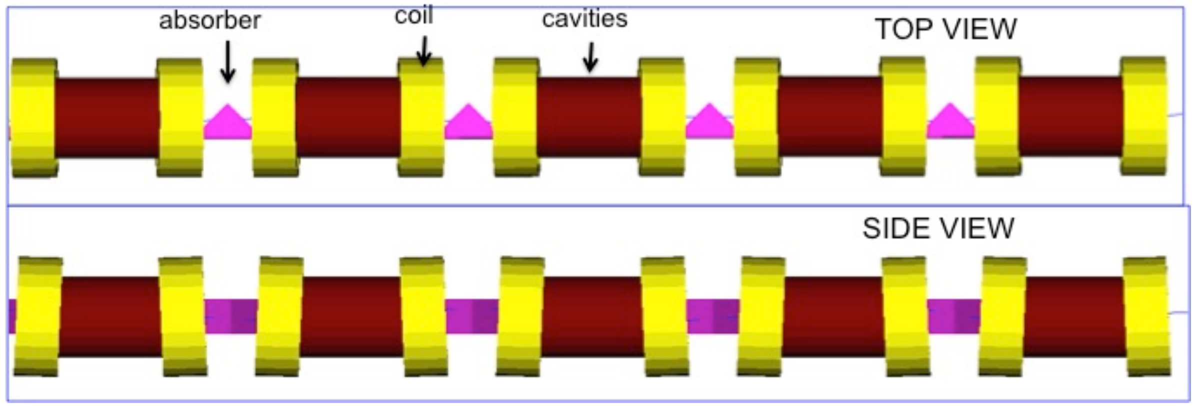


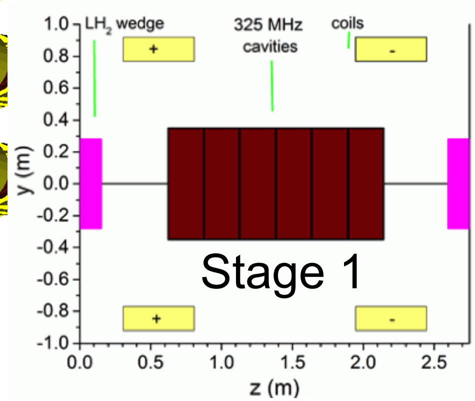


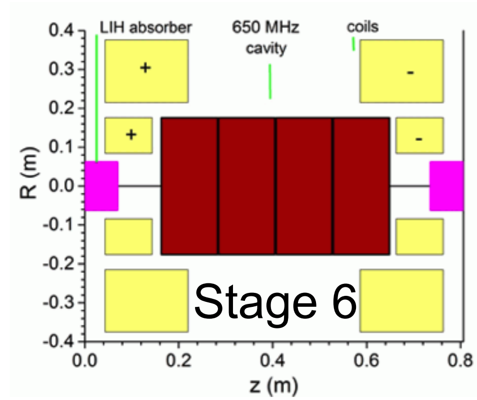
- Helical FOFO snake channel for initial cooling.
- Cools both signs of muons simultaneously.
- Solid wedge absorbers (LiH) + gas-filled RF cavities (GH2).
- 6D emittance: 5.6 (μ^-) and 6.2 (μ^+) cm^3 to 0.051 cm^3.

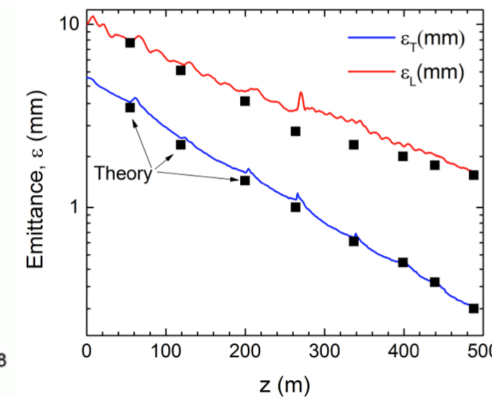
Vacuum RF cooling channel (VCC)





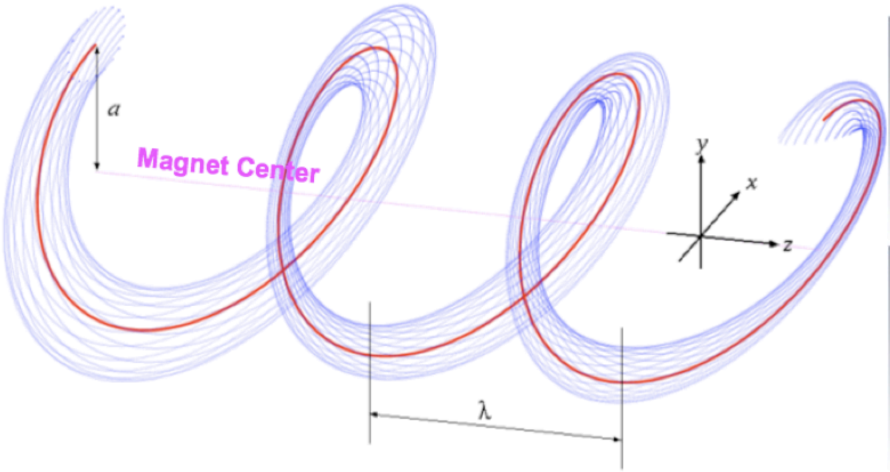




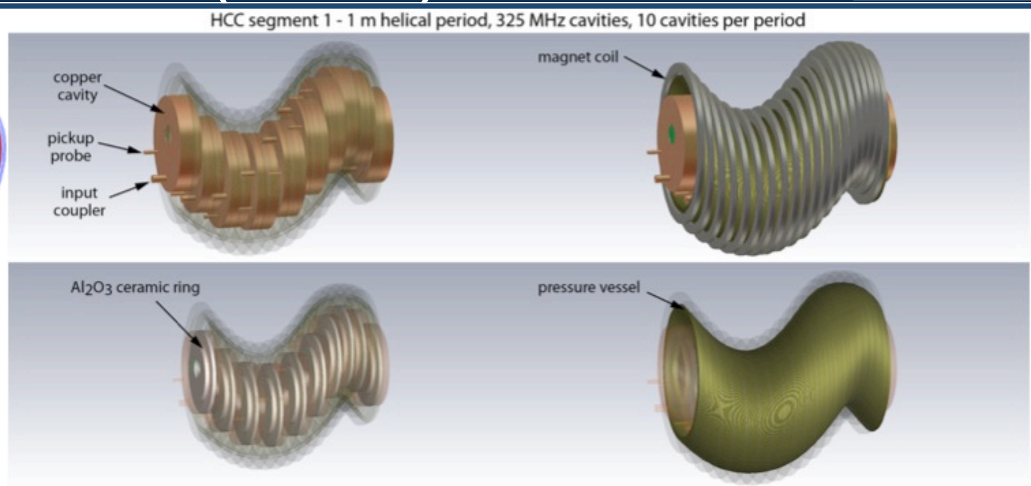


- Rectilinear vacuum RF 6D cooling channel (VCC).
- Multi-stage (8 stages) tapered channel with LH2 or LiH wedge absorbers.
- Single charge cooling.
- Two basic frequencies: 325 and 650 MHz.
- Final transverse emittance is 0.28 mm, longitudinal – 1.5 mm.

High-pressure gas-filled cooling channel (HCC)



Typical beam path in a HCC

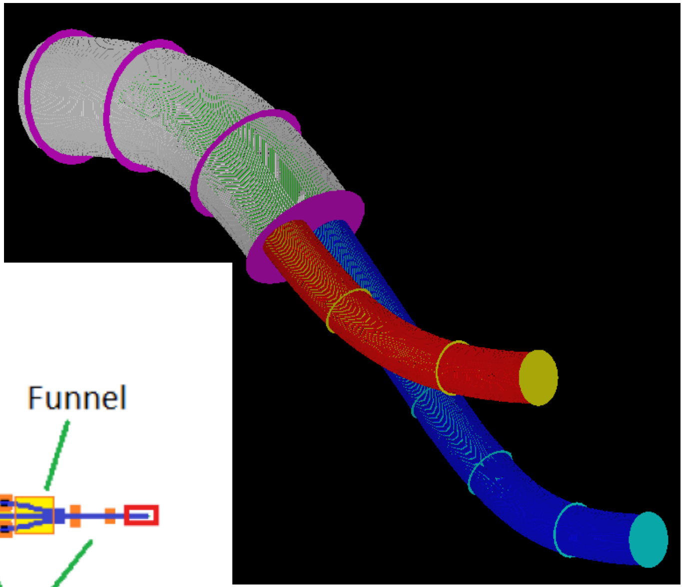


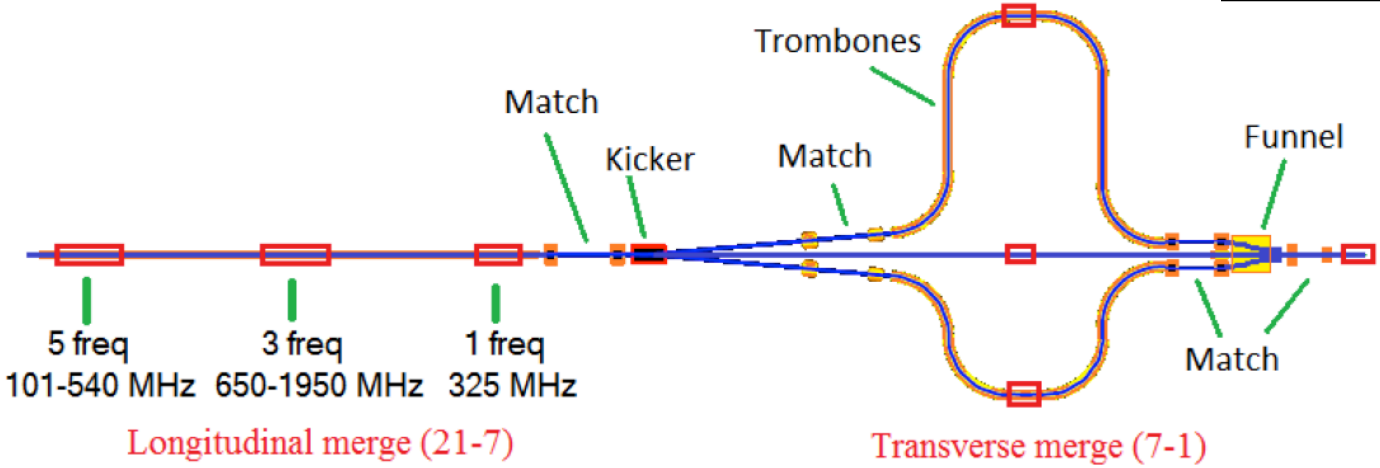
Conceptual design of the HCC

- Helical high-pressure gas-filled cooling channel (HCC).
- Continuous GH2 absorber.
- Solenoid + helical dipole (define reference trajectory) + helical quadrupole (control dispersion, provide transverse stability).
- Multi-stage (4 stages) tapered channel: helical period decreases, RF frequency increases (325➔650➔975 MHz).
- High pressure gas reduces the probability of electric breakdown in the RF cavity, allows higher operating E fields in strong magnetic fields.

Charge separation and bunch merge

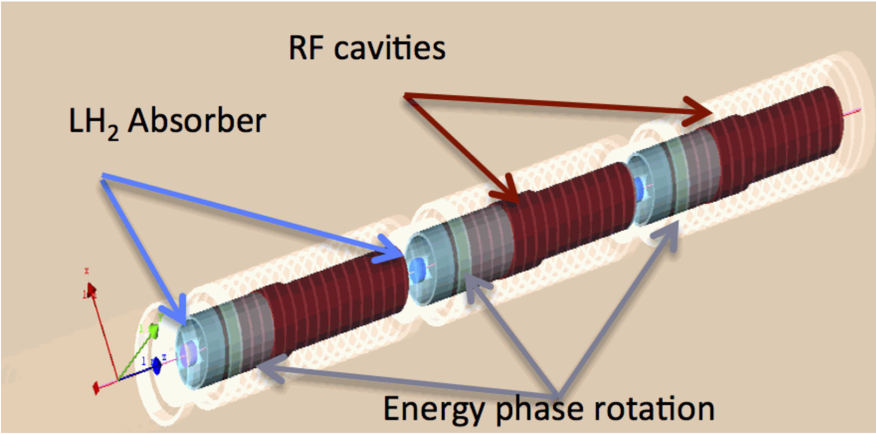
- Charge separation section concept. Separates charges after initial cooling.
- Can be used by HCC or VCC.



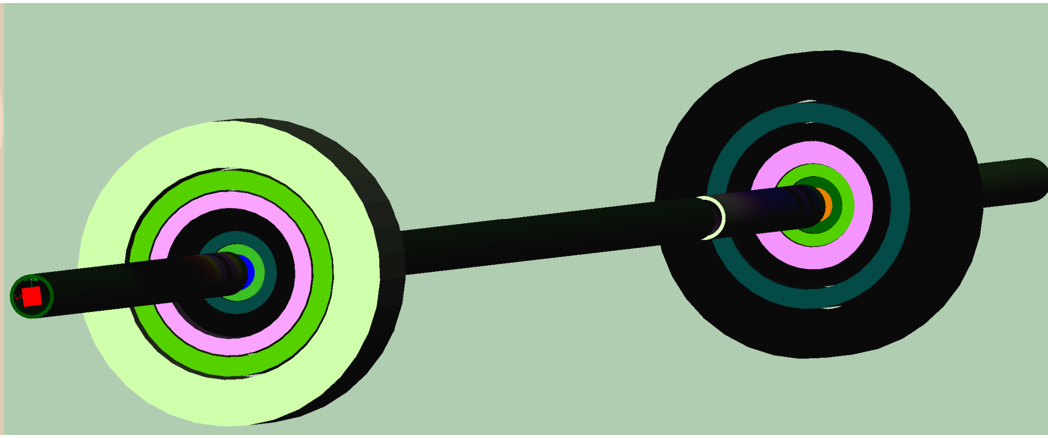


- Bunch merge section concept (VCC). Merges 21 bunches into 7 longitudinally then 7 into one transversely. Combines bunches after some 6D cooling.
- Overall transmission ~78%, emittance grows from 1.6 to 6.8 mm.

Final cooling channel



Early stages: RF inside transport solenoid coils

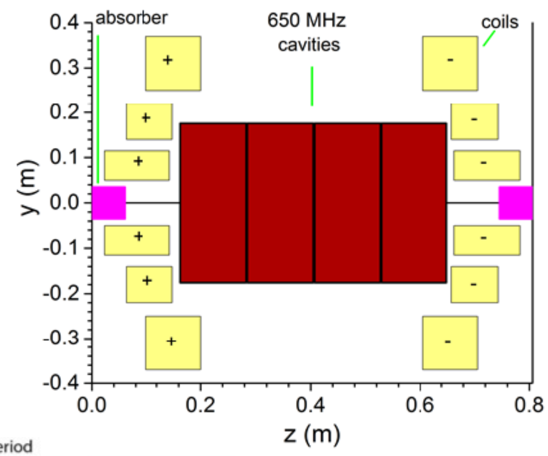


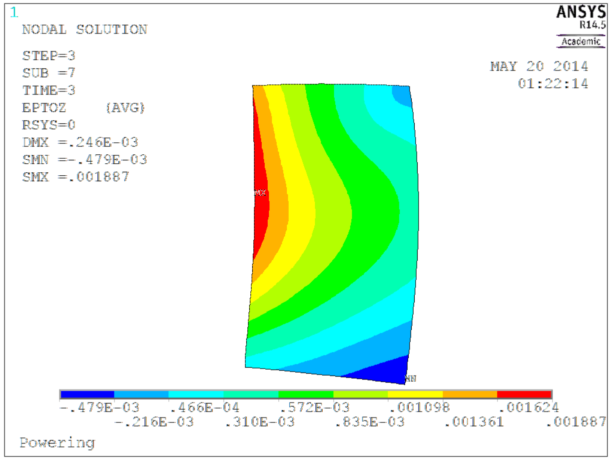
Late stages: transport solenoid coils inside induction linac

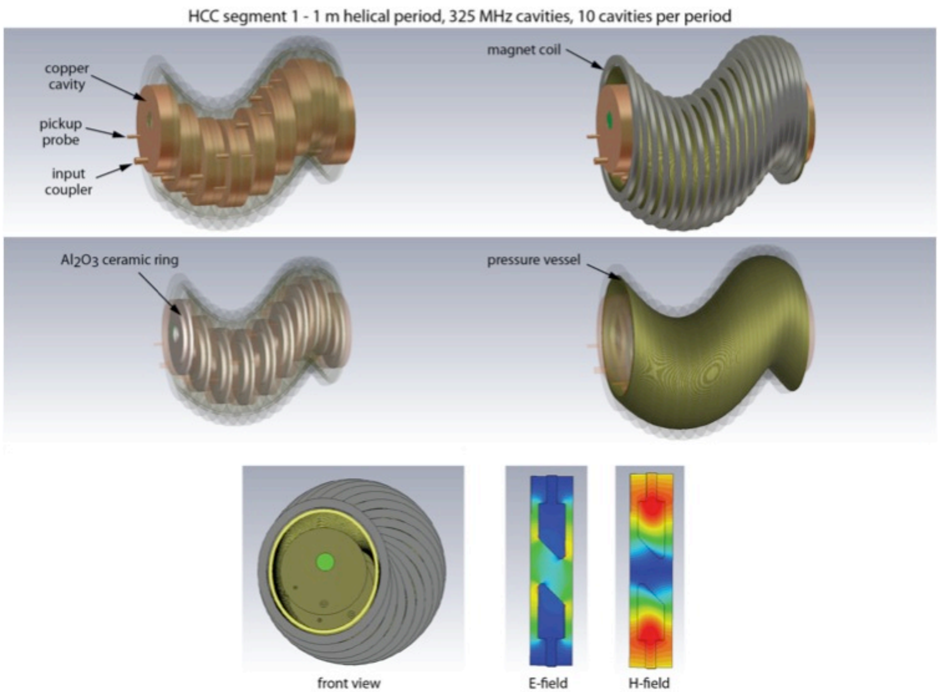
- Final cooling channel design with 30-25 T focusing field.
- Preliminary results for a complete design of a high field cooling channel: transverse emittance 55 μm, longitudinal ≈75 mm. (40 T could reach 25 μm.)
- Field flip frequency under study.
- I'm sure there will be more details in Hisham Sayed's talk later in the session.

Key issue: magnet design, component integration

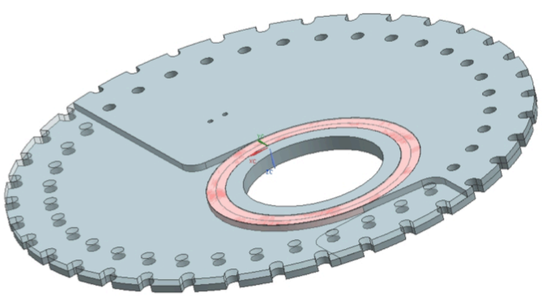
- VCC: demanding magnet configuration, especially toward the latter stages.
- Azimuthal strain in the inner solenoid (0.19%) is within Nb_3Sn irreversible limit (0.25%).





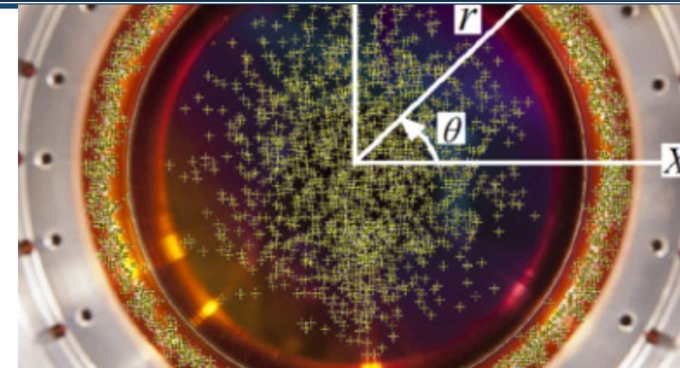


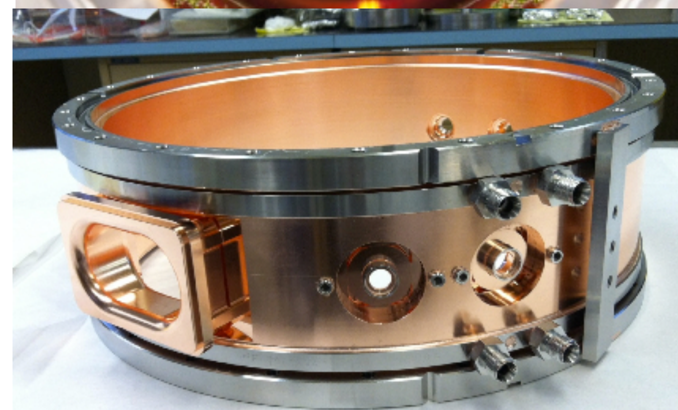
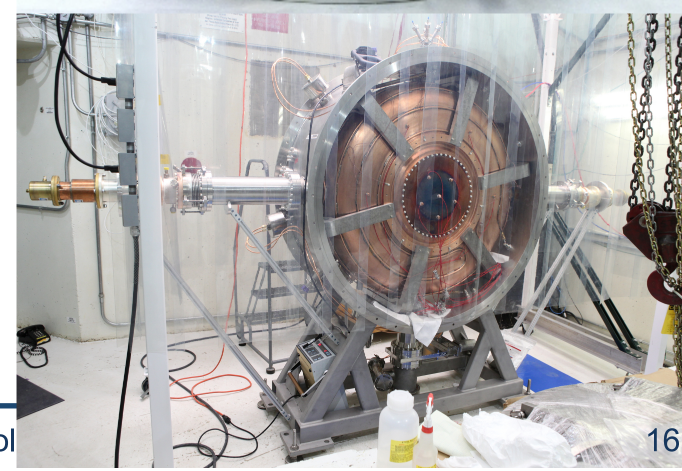
- HCC: integration of RF and helical solenoid.
- Obtaining the right ratio between solenoidal, helical dipole and helical quad components.



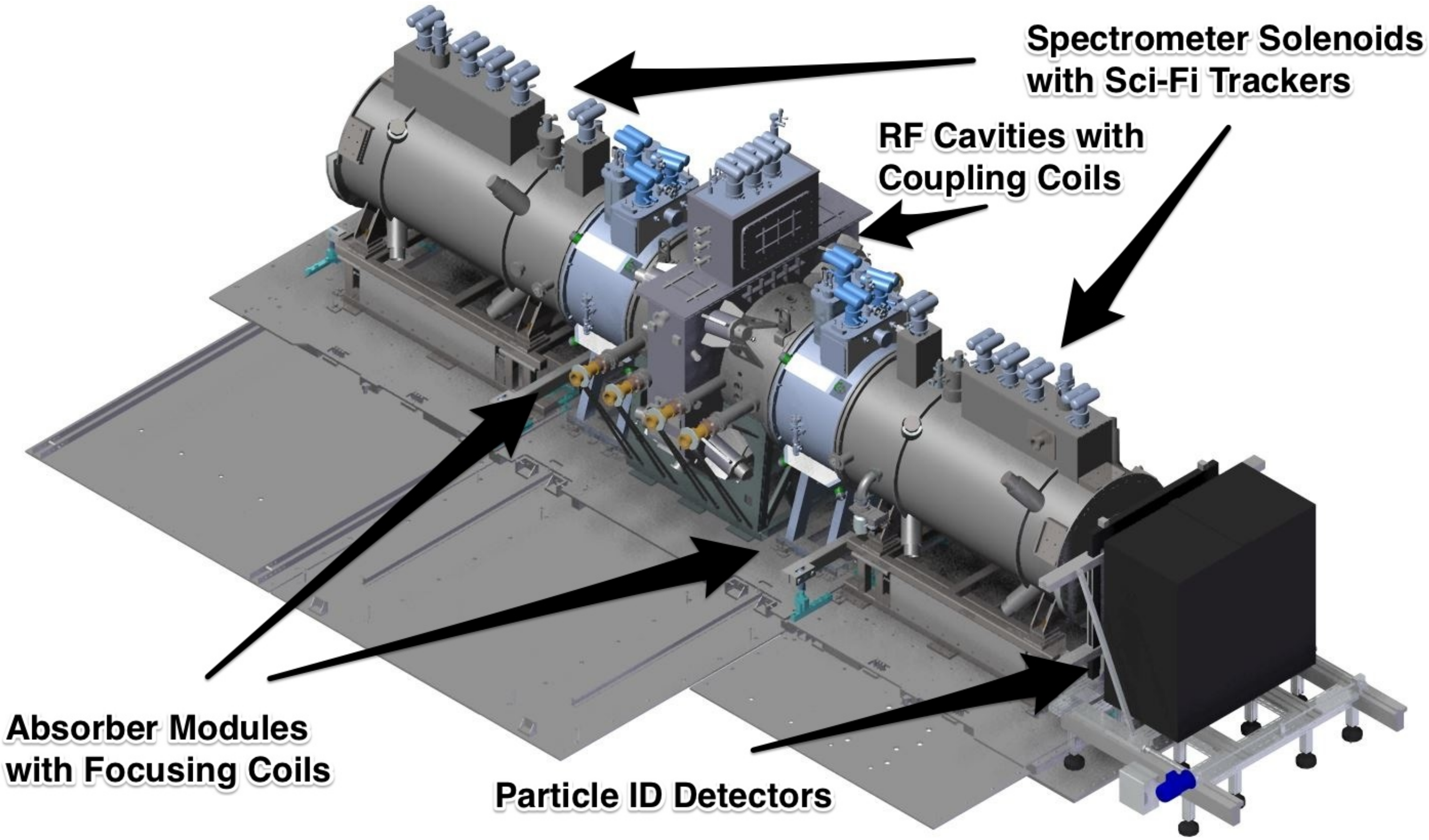
Key issue: RF breakdown

- Muon cooling channels require RF operation in strong magnetic fields.
- Gradients are known to be limited by RF breakdown.
- Extensive experimental program underway at the MuCool Test Area (MTA) at Fermilab.
- Encompasses both vacuum and high-pressure RF.
- Multiple cavities with different surface materials/treatments tested under a variety of conditions.
- Among those being tested is a 201 MHz single-cavity Muon Ionization Cooling Experiment (MICE) module.



MICE



- International Muon Ionization Cooling Experiment (MICE) underway at RAL (UK).
- Step IV construction is at an advanced stage:
- Step V (sustainable cooling) configuration is shown.

MICE

- Step IV construction is at an advanced stage:
  - Both SciFi trackers have been fabricated and tested.
  - Both spectrometer solenoid magnets are at RAL.
  - The first AFC magnet has been trained for Step IV.
  - The LH2 absorber has been built and the delivery system tested.
  - The next challenge is to combine the subsystems in the beam line with suitable magnetic shielding.
- The construction of MICE Step V (sustainable cooling) is well underway:
  - All RF cavities and windows for the RFCC module have been fabricated.
  - An electropolished cavity is being outfitted for tests at the MTA and the large coupling coil has been tested and accepted.
- Overall, MICE is progressing towards the first experimental study of muon ionization cooling. Step IV is planned for 2015 and the concluding Step V may be ready as soon as 2017.

Summary

- Systematic study of six-dimensional cooling and the corresponding D&S effort are underway.
- End-to-end simulations indicate that the desired emittances are achievable in all cases of interest.
- D&S group works in constant contact with other groups (magnets, RF) to ensure the designs are realistic.
- RF breakdown issue is being studied, mitigation strategies are being developed (MTA).
- MICE muon ionization cooling demonstration is imminent.

Thank you!

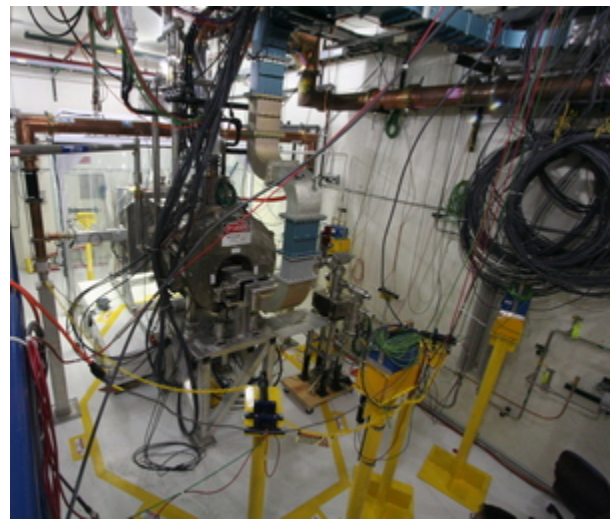
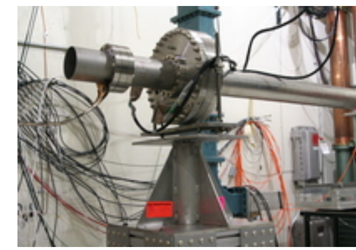
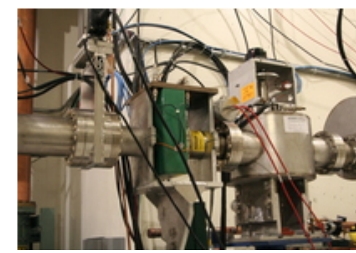
Backup slides

MuCool Test Area
http://mice.iit.edu/mta/

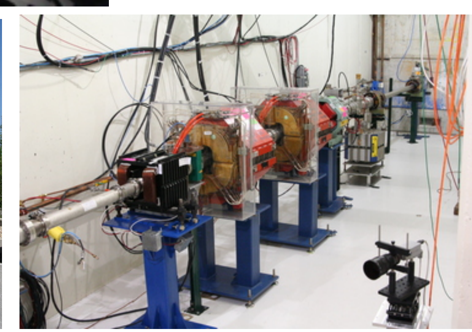
Dedicated facility at the end of the Linac at FNAL for muon cooling R&D

- RF power at 2 frequencies
  - 12/4.5 MW @ 805/201 MHz
- Large-bore 5T SC solenoid
- LHe cryogenic plant
- 400-MeV H- beamline and instrumentation
- Class-100 portable clean room
- H2 safety infrastructure
- Extensive diagnostics for RF cavity tests
- ***Unique in the world***







Slide from the presentation by Y. Torun at the MAP collaboration meeting, May 30, 2014

Muon Accelerator Staging Study (MASS)